On-line Fault diagnosis of Arbitrary Connected Networks

Arunanshu Mahapatro[1], Pabitra Mohan Khilar[2]
Department of Comp. Sc. & Engg, NIT, Rourkela, India, Pin-769008
Email: [1]arun227@gmail.com, [2]khilarpm@yahoo.com

***Abstract*— This paper proposes an on-line two phase fault diagnosis algorithm for arbitrary connected networks. The algorithm addresses a realistic fault model considering crash and value faults in the nodes. Fault diagnosis is achieved by comparing the heartbeat message generated by neighboring nodes and dissemination of decision made at each node. Theoretical analysis shows that time and message complexity of the diagnosis scheme is O(*n*) for a n-node network. The message and time complexity are comparable to the existing state of art approaches and thus well suited for design of different fault tolerant wireless communication networks..**

***Index Terms*— On-line diagnosis, two phase diagnosis, value faults, dynamic fault environment.**

I. Introduction

The distributed arbitrary connected networks such as mobile ad hoc network and sensor network are becoming popular due to their extensive use in social, commercial and scientific applications. These networks may be deployed in unattended and possibly hostile environments. The hostile environment affects the monitoring infrastructure and nodes become more susceptible to component failures. Incorporating correct and timely fault diagnosis capability to the system with less overhead is essential to improve the system reliability and availability. An important element for the timeliness of online diagnosis is the ability to execute diagnostic tests without interrupting system operation, that is, without explicit testing capabilities. A well-known solution is the comparison approach, where multiple nodes execute the same task, and the outcomes are compared by other nodes [1][2]. The agreements and the disagreements among the nodes are the basis for identifying the faults. This paper follows this diagnosis approach where heartbeat messages are broadcasted periodically. In distributed self-diagnosis, every node in the network needs to record the status of all other nodes.

Motivated by the need a two-phase on-line distributed diagnosis approach for arbitrary connected networks is proposed. A synchronous system model is chosen for simplicity of presentation where a distributed system framework by using a round-based (synchronous) message dispersal protocol is considered. The diagnostic latency and message complexity is used as the performance measure in order to evaluate the proposed fault diagnosis algorithm. A typical scalar wireless sensor network is considered as an arbitrary network and the performance of the proposed algorithm is evaluated by simulation.

The specific contributions of this paper are listed as follows:
1. Proposes a generic diagnosis scheme that identifies crash and value faults with high accuracy by maintaining low time, message and energy overhead.
2. Presents both analytical and simulation analysis to prove the correctness and completeness of the algorithm.

II. Related Works

System-level fault diagnosis was introduced by Preparata, Metze and Chien in 1967 [3], as a technique intended to diagnose faults in a wired inter connected system. Previously developed distributed diagnosis algorithms were designed for wired networks [1–4] and hence not well suited for wireless networks. The problem of fault detection and diagnosis in wireless networks is extensively studied in literatures [5–11]. The problem of identifying faulty nodes (crashed) in WSN has been studied in [5]. This article proposes the WINdiag diagnosis protocol which creates a spanning tree (ST) for dissemination of diagnostic information. Thomas et al. [6] have investigated the problem of target detection by a sensor network deployed in a region to be monitored. The performance comparison was performed both in the presence and in the absence of faulty nodes. Elhadef et al. have proposed a distributed fault identification protocol called Dynamic-DSDP for MANETs which uses a ST and a gossip style dissemination strategy [7]. In [8], a localized fault diagnosis algorithm for WSN is proposed that executes in tree-like networks. The approach proposed is based on local comparisons of sensed data and dissemination of the test results to the remaining sensors. In [9] the authors present a distributed fault detection algorithm for wireless sensor networks where each sensor node identifies its own state based on local comparisons of sensed data against some thresholds and dissemination of the test results. The fault detection accuracy of a detection algorithm would decrease rapidly when the number of neighbour nodes to be diagnosed is small and the nodes failure ratio is high. Krishnamachari et al. have presented a Bayesian fault recognition algorithm to solve the fault-event disambiguation problem in sensor networks [10].

III.SYSTEM AND FAULT MODEL

A. System Model

The communication network is assumed to be error-free, and deliver messages reliably. We consider a round-based communication model, which implies that periodically, i.e., at the period boundaries, messages are sent by system nodes.

DOI: 01.IJNS.03.01.88

The system under consideration accommodates *n* number of nodes. Each node occupies a position (*x*, *y*) inside of a fixed geographic area ($l \times l\ m^2$) and are initially uniformly distributed. Two nodes v_i and v_j are within transmission range R_{tx}, if the Euclidean distance $d(v_i, v_j)$ is less than R_{tx}. The topology graph G = *(V,E)* consists of a set of vertices *V* representing the nodes of the network and the set *E* of undirected edges corresponding to communication links between nodes. Each node in the network maintains a neighbor table *N(.)* which stores IDs of 1-hop neighbors. All nodes execute the same workload (For example temperature sensing from the environment) and determine the output value x_i. This value is communicated to all other nodes. An arbitrary network with connectivity *k* has been assumed. Every node is assigned with a node-ID, and can detect the absence or time deviance for an expected message.

B. Fault Model

We consider crash and value faults in nodes. Links are assumed to be fault free. A crash-faulty node is unable to communicate with the rest of the network, whereas a node with value fault continues to operate and communicate with unpredicted behavior. These malfunctioning (value faulty) sensors could participate in the network activities since still they are capable of routing information.

C. Time Synchronization

The proposed algorithm needs to synchronize since sensor readings at diagnosis interval are exchanged to establish a protocol for correct and complete diagnosis. One of the key lightweight time synchronization in WSNs is Timing-sync Protocol for Sensor Networks (TPSN)[12]. TPSN generates time synchronization with periodic time synchronization messages. TPSN maintains a global time in the network by organizing the system into levels. Level discovery is performed at the initial time when the network is deployed. The sink is the root of the network. It is assigned a level 0. A node at lower level accepts the *time sync packets* from nodes in the upper level and drops all other *time sync packets* from its lower level and the peers in the same level. Finally the whole WSN will follow the clock of the sink.

This work has modified the original TPSN for diagnosis settings. This work uses UDG-NNT algorithm [13] to construct a ST where each node is assigned a rank. The sink node has the highest rank in the network. Each node v_i, except sink node, selects the nearest node v_j among its neighbor nodes such that $rank(v_i) < rank(v_j)$ and sends a connect message to v_j to inform that (v_i, v_j) an edge in the ST. This work introduces a level maintenance phase which ensures a connected ST. Therefore, creating and maintaining a hierarchical structure should not be considered as an overhead exclusive to the diagnosis algorithm.

IV. The Algorithm

This work considers two fault categories: 1) The set of *missing messages*, are those messages which node v_i believes node v_j failed to issue and 2) The set of *improper logical messages*, are those messages which are correctly delivered but disagree with x_i, the result of v_i's own voting process on messages received. A formal description of the detection algorithm is presented in Algorithm 1.

Algorithm 1: Detection algorithm

First phase
1. Broadcast the test message
2. Set timer for T_{out}
3. If T_{out} = true then
4. Detect unreported nodes as hard faulty.
5. Obtain the sensor readings of all neighbours.
6. If v_i agrees with v_j (v_j is element of $N(v_i)$).
7. Detect v_j fault free.
8. Repeat step 6 and 7 for all v_j, $j=1,..,|N(v_i)|$ and generate local fault table.
9. Broadcast this local fault table.

Second phase
10. Upon receiving the local fault tables from 1-hop neighbors v_i compares the local fault tables.
11. If more than half of the reported nodes mark v_j faulty then v_i finally detect v_j faulty.

Out of the two phases of the algorithm, during the first phase each node periodically execute the diagnostic work load and initiates the results by a round of message transmissions to all other nodes. A node detects a crash or missing message fault without receiving a test message before Tout. If the message delivery and its arrival at a receiving node is valid but incorrect (i.e., readings does not match with its own reading), the message is recorded as improper logical message and the node is value faulty. This phase of diagnosis we call local diagnosis phase. In this phase a node identifies 1-hop neighbor node's validity by comparing its own message with that of received message.The comparison need not seek for an exact value in the message rather can choose to consider range or deviance check. If the received message is well within the range of its own value, it accepts as a correct message otherwise records as incorrect message. An adversary node may also send an erroneous message in its header, which may not be detectable during this phase. We show that, these faults are detected by the second phase of diagnosis. In the second phase these local results available at each node are further exchanged with other nodes and a counter maintained at every node is incremented by one for every positive diagnosis. If the counter value at a particular node for another node is greater than half of the nodes, it means that more number of nodes detected that node as faulty and all othernodes that recorded this event as fault free is accused as faulty. If the accusation against a node is recorded as faulty in the previous round, this node is considered as faulty in the current round. Both the phases of two-phase diagnosis procedure are executed in a pipelined manner to improve diagnostic latency.

The primary fault table of a node v_i, $FT_p(v_i)$, represents the union of test outcomes due to improper logical message andmissing message in first phase. The table entry corresponding to any node v_j *Î* $N(v_i)$ is a binary input: 0

DOI: 01.IJNS.03.01.88

corresponds to a fault-free input received from v_j as perceived by v_i, and 1 represents a fault being perceived by v_i. In the second phase this work defines a function $f_{vi}(v_j) = |UFT_p(v_i)|$ where v_i *Î* $N(v_j)$. This function is used to count the number of accusations on a processor v_j by all other. Thus $f(v_j)$ is an integer where *0 £* $f(v_j)$ *£ (n-1).*

The local diagnostic views are disseminated to obtain a global diagnostic view of the network. Once ST maintenance is completed the leaf nodes in ST start dissemination phase by sending their local diagnostic view to their parent. Once sink node has the global diagnosis view the synchronization phase is triggered and the global view is embedded in the time sync packet of sink node. Thus, at the end of synchronization phase all nodes in the network have the global view of the network.

IV. Basic Analysis of Algorithm

The formal analysis of algorithm involves satisfying the two important properties as follows:

Correctness: every node diagnosed to be faulty by a non-faulty node is indeed faulty.

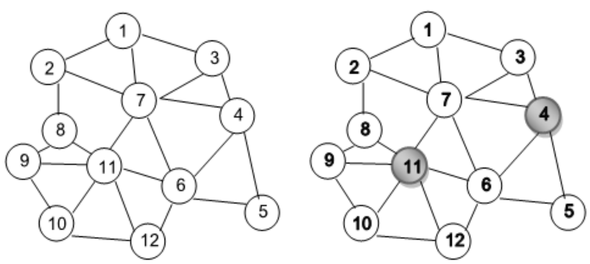

Fig1. Example to show correctness of the algorithm

Completeness: Every faulty node is identified.

First, we consider correctness, which states that if a good processor accuses some other processor, the accused processor is indeed faulty.

Theorem1. (Correctness). If a node vi is faulty, then all fault free nodes diagnose vi as faulty.

Proof. The only situation in the algorithm that a good node vi could declare another node faulty when fvi(vj) ³[|N(v_i) N(v_j)|/2]. For easy understanding of the proof we consider an example shown in Fig.1. Let node 6 represents vi and node-7 represents vj. Fig1.a assumes all neighbor nodes of node-6 and node-7 are fault free. These two nodes share node-11 and node-12 as their common neighbors.Here node-6 correctly detects node-7 as fault free since $f_6(7) \geq [|N(6) \cap (7)|/2]$ .In scenario as depicted in Fig.1.b node-6 receives positive remarks only from node-7 and thus $f_6(7)$ < [|N(6))” N(7)|/2]. Thus node-6 incorrectly detects node-7 as faulty.However, node-1 detects node-7 as fault free since $f_1(7)$ ³ [é|N(1))” N(7)|/2] . In the dissemination phase each node sends its local diagnostics to the node in upper level.Thus the incorrect decisions taken by nodes are taken care by the nodes at the higher level and finally the diagnostic information in sink node at the end of local dissemination contains the exact set of fault set.

The upper bound time complexity is expressed in terms an upper bound on the time (*Tp*) needed to propagate a message between sensor nodes.

Theorem2. (Completeness).The diagnosis algorithm terminates before a bounded delay $T_{complexity} = (2n-1)T_p + 2T_{out} + T_{processing}$

Proof. The detection phase takes at most $2T_{out}+T_{processes}$ time in obtaining the local diagnostic view. $T_{processes}$ is the time taken by nodes to process the diagnosis massage. In ST maintenance phase, the node with faulty parent needs at most $3T_p$ time to get connected with ST. In at most $d_{st}T_p$, the sink node obtains the global diagnostic view of the network where d_{st} is the depth of ST. The sink node disseminates this view that reaches the farthest node in at most $d_{st}T_p$. In worst case d_{st} = *n “ 1*. Now, the upper bound time complexity can be expressed as

$$T_{complexity} = (2n-1)T_p + 2T_{out} + T_{processing}$$

Theorem3. The proposed algorithm has a worst-case message exchange complexity O(*n*) in the network.

Proof: In the first phase each node sends the diagnostic message to its neighbors, costing one message per node i.e. *n* messages in the network. Similarly, in the second phase *n* number of diagnostic messages is exchanged.

Building the ST with sink as root costs at most *2n* message exchange. Each node, excluding the sink, sends one local diagnostic message. Each node, excluding the leaf node, sends one global diagnostic message and in worst case depth of ST is *n-1*. Thus, message cost for disseminating diagnostic messages is *2*(*n-1*). So, the total number of exchanged messages is

$$M_{cost} = 6n-2 = O(n)$$

V. Simulation Results

The performance of the proposed scheme via simulations is presented in this section. This work uses OMNET++ as the simulation tool where all simulations are conducted on networks using the IEEE 802.15.4 at the MAC layer. The set of simulation parameters are summarized in Table 1.

TABLE1. SIMULATION PRAMETERS

Parameter	Value
Number of nodes	100-1000
Network grid	From (0, 0) to (1000, 1000)
Sink	At (75,150)
Simulation time	300 Sec
Propagation scheme	Two Ray Ground
Antenna scheme	Omni directional

Fig. 2 shows the communication complexity of the proposed protocol. From the simulation result it is evident that the communication complexity of this work outperforms thepresent state of art schemes. Energy consumption by each node is proportional to the amount of traffic it generates or receives. Thus, the energy overhead of the proposed scheme is less which in turn improves the network lifetime of a WSN.

DOI: 01.IJNS.03.01.88

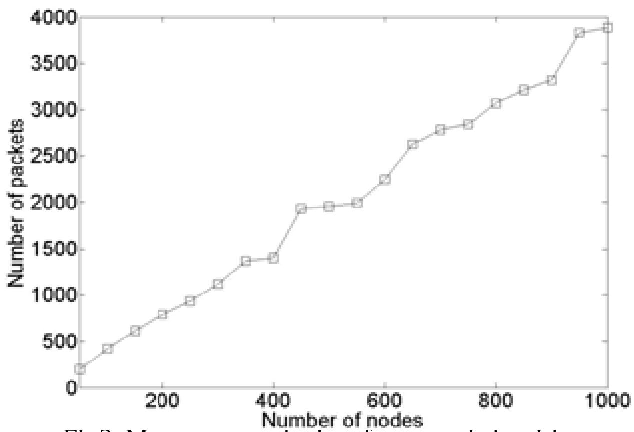

Fig2. Message complexity of proposed algorithm

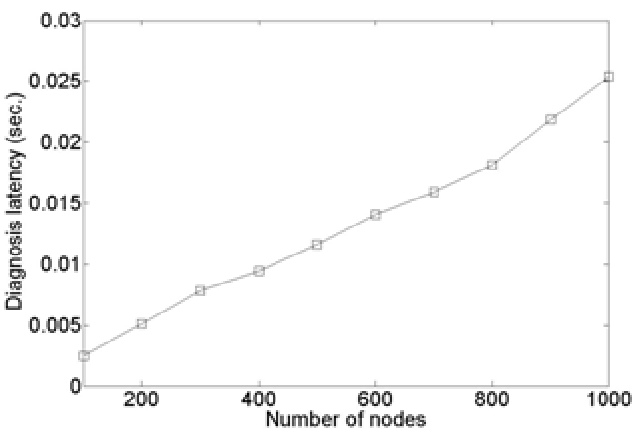

Fig3. Time complexity of proposed algorithm

Fig. 3 demonstrates the time complexity of the proposed scheme. From Theorem 2 it is obvious that dissemination of diagnostics contributes more to diagnosis latency. The depth of the ST decides the diagnosis latency, as it is used to disseminate diagnostics. Thus, as expected the time required to diagnose the WSN increases almost linearly with increase of number of nodes.

Conclusions

This paper presents a diagnosis scheme to address the fundamental problem of identifying faulty (value and crash)nodes in a arbitrary connected network. The proposed work assumes that at most α number of nodes are faulty at any time t where α is connectivity of the network. However, if more than α number of nodes are faulty then detection accuracy in obtaining local view is less affected. The global view is severely affected since the network gets partitioned. The message and time complexity of the proposed model is O(*n*) which is significantly low compared to present state of art approaches. Due to low message and time complexity the model could be integrated to fault tolerant systems.

References

[1] M. Malek, "A comparison connection assignment for diagnosis of multiprocessor systems." ACM, 1980, pp. 31 – 36.

[2] A. Sengupta and A. Dahbura, "On self-diagnosable multiprocessor systems: diagnosis by the comparison approach" , IEEE Transactions on Computers,, vol. 41, no. 11, pp. 1386 – 1396, nov. 1992.

[3] F. P. Preparata, G. Metze, and R. T. Chien, "On the connection assignment problem of diagnosable systems," IEEE Transactions on Electronic Computers, vol .EC-16, no. 6, pp. 848 –854, dec. 1967.

[4] A. Subbiah and D. Blough, "Distributed diagnosis in dynamic fault environments,"IEEE Transactions on Parallel and Distributed Systems, vol. 15, no. 5, pp. 453 – 467, may 2004.

[5] S. Chessa and P. Santi, "Crash faults identification in wireless sensor networks, Computer Communications, vol. 25, no. 14, pp. 1273 – 1282, 2002.

[6] M. Elhadef, A. Boukerche, and H. Elkadiki, "A distributed fault identification protocol

[7] for wireless and mobile ad hoc networks," Journal of Parallel and Distributed Computing, vol. 68, no. 3, pp. 321 – 335, 2008.

[8] X. Xu,W. Chen, J. Wan, and R. Yu, "Distributed fault diagnosis of wireless sensor networks," in ICCT, nov. 2008, pp. 148 –151

[9] M.-H. Lee and Y.-H. Choi, "Fault detection of wireless sensor networks," Computer Communications, vol. 31, no. 14, pp. 3469 – 3475, 2008.

[10] B. Krishnamachari and S. Iyengar, "Distributed bayesian algorithms for faulttolerant event region detection in wireless sensor networks," IEEE Transactions on Computers, vol. 53, no. 3, pp. 241 – 250, mar. 2004.

[11] J. Chen, S. Kher, and A. Somani, "Distributed fault detection of wireless sensor networks," in *DIWANS*. ACM, 2006, pp. 65–72.

[12] Ganeriwal, S.; Kumar, R.; Srivastava, M.B. Timing-Sync Protocol for Sensor Networks. In Proceedings of the 1st International Conference on Embedded Networked Sensor Systems, SenSys 2003, Los Angeles, CA, USA, 5–7 November 2003; pp. 138-149.

[13] M. Khan, G. Pandurangan, and V.S. Anil Kumar. Distributed algorithms for constructing approximate minimum spanning trees in wireless sensor networks. IEEE Transactions on Parallel and Distributed Systems, 20(1):124 –139, 2009.

DOI: 01.IJNS.03.01. 88